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# Thermal versus Direct $J/\Psi$ Production in Ultrarelativistic Heavy-Ion Collisions

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The production of  $J/\Psi$  mesons in central collisions of heavy nuclei is investigated as a function of collision energy. Two contributions are considered simultaneously: early (hard) production coupled with subsequent suppression in a Quark-Gluon Plasma, as well as thermal recombination of primordially produced  $c$  and  $\bar{c}$  quarks at the hadronization transition. Whereas the former still constitutes the major fraction of the observed  $J/\Psi$  abundance at SpS energies, the latter dominates the yield at RHIC. The resulting excitation function for the number of  $J/\Psi$ 's over open charm pairs exhibits nontrivial structure around  $\sqrt{s} \simeq 30$  AGeV, evolving into a significant rise towards maximal RHIC energy. We study this feature within different (thermal) scenarios for  $J/\Psi$  suppression, including parton-induced quasifree destruction as a novel mechanism.

A promising probe for hot and dense QCD matter as created in the early phases of heavy-ion reactions is the abundance of  $J/\Psi$  mesons, measured via their decay branching into dilepton final states. Their production is expected to be significantly reduced in the case of Quark-Gluon Plasma (QGP) formation in sufficiently energetic collisions of large nuclei. In such a picture,  $J/\Psi$  mesons are exclusively formed primordially (*i.e.*, upon first impact of the colliding nucleons), and subsequently dissociated by (i) nuclear absorption, (ii) parton-induced destruction in a QGP [1] and/or Debye screening [2], and (iii) inelastic scattering on “comoving” hadrons in the final hadron gas phase of the reaction. The identification of the plasma effect thus requires a reliable knowledge of both (i) and (iii). Nuclear absorption is appreciable and has been thoroughly investigated in  $p$ - $A$  and light-ion reactions, whereas the impact of hadronic interactions is not yet well under control, although its net effect seems to be rather moderate, see, *e.g.*, Refs. [3–7]. Within this framework the data of the NA50 collaboration at the SpS have been interpreted as evidence for QGP formation in the most central  $Pb(158 \text{ AGeV})$ - $Pb$  collisions [8].

Recently, an alternative view of  $J/\Psi$  production in heavy-ion reactions has been put forward. Prompted by the observation that the  $J/\Psi$  yield per charged hadron is remarkably constant as a function of impact parameter, it has been argued in Ref. [9] that all  $J/\Psi$ 's are created statistically at the hadronization transition. The deduced temperature of  $T \simeq 175$  MeV is well in line with the so-called chemical freeze-out of *light* hadron production [10–12]. However, no reference is made to an underlying mechanism for  $c\bar{c}$  creation. In a somewhat different approach, Braun-Munzinger and Stachel have extended their thermal model analysis [10] to include (open and hidden) charm hadrons [13] (see Ref. [14] for an update of this analysis). Together with the (dynamically well justified) proposition that  $c\bar{c}$  pairs at SpS energies are exclusively produced primordially, the  $J/\Psi$  abundance in sufficiently central  $Pb$ - $Pb$  collisions can be accounted for by statistical recombination of  $c$  and  $\bar{c}$  quarks at the earlier inferred hadro-chemical freeze-out without introduction of new parameters. In a subsequent analysis [15],

this approach was reiterated using a more complete set of charmed hadrons and enforcing exact (local) charm conservation within a canonical-ensemble treatment. Requiring to reproduce the NA50 measurements for  $J/\Psi$  production, an open-charm enhancement factor of  $\sim 3$  relative to  $N_p^{4/3}$  times the value in  $N$ - $N$  collisions was deduced for central  $Pb$ - $Pb$  collisions ( $N_p$ : number of participant nucleons). This coincides with the enhancement needed to explain the NA50 intermediate-mass region (IMR) dilepton spectra solely in terms of increased open-charm production\*. As first pointed out in Ref. [13], the application of the thermal production framework to RHIC energies could in fact lead to an enhancement of  $J/\Psi$ 's over its primordial production rate (see also Ref. [18]).

One of the main assumptions in the thermal model analyses is that primordial production of  $J/\Psi$ 's is absent, *i.e.*, they either do not form or are fully suppressed before the hadronization transition. Under SpS conditions with supposedly rather short plasma lifetimes of 1-2 fm/c, this assertion is, however, not easily realized. In this article we therefore attempt a combined description of thermal and primordial production, the latter being subjected to nuclear absorption and plasma dissociation in an expanding fireball model around midrapidities. The focus will be on central  $Pb$ - $Pb$  ( $Au$ - $Au$ ) collisions at varying  $\sqrt{s}$  energy, covering the SpS and RHIC regime. We fix the participant number at  $N_p \simeq 360$  (corresponding to an impact parameter  $b \simeq 1.5$  fm) to avoid complications associated with transverse-energy fluctuations in the most central collisions [19–21]. Also,  $c\bar{c}$  pairs will be allowed to coalesce into charmonium states only over a limited range of rapidities.

Let us start by discussing our implementation of the contribution from primordial production and subsequent

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\*In this paper we adopt a scenario without any “anomalous” open-charm enhancement, attributing the NA50 IMR dilepton excess to thermal radiation [16,17].

suppression. As in Ref. [13], we assume that the production of  $c\bar{c}$  pairs entirely occurs in primary (hard) nucleon-nucleon collisions (secondary creation in a partonic medium has been shown to be negligible even at full RHIC energy [22]). In free space a certain fraction  $F_\Psi$  of these pairs combines into a final number  $N_{J/\Psi}^{dir}$  of directly produced  $J/\Psi$  mesons ( $F_\Psi \simeq 2.5\%$  in the SpS energy regime [23]). In a heavy-ion environment, the first phase of suppression is characterized by interactions of the (pre-resonant) bound state with interpenetrating nucleons. It leads to a rather well understood  $(N_{p1}N_{p2})^\alpha$  suppression of the cross section with  $\alpha = 0.92 \pm 0.01$  as inferred from  $p$ - $A$  and  $A$ - $B$  reactions with light projectile nuclei (see also Ref. [24]). This factor equally applies to other charmonium states ( $\chi_c$ ,  $\Psi'$ ), which contribute via their decay branchings into  $J/\Psi + X$  final states (“feed-down”). We model this so-called nuclear absorption using a Glauber model with a phenomenological constant cross section  $\sigma_{\Psi N} \simeq 5.8$  mb [25].

In the second phase of suppression – the QGP – charmonium destruction has been discussed in both static screening-type pictures as well as dynamical ones via inelastic collisions with partons, most notably the QCD analogue of photo-dissociation,  $g + J/\Psi \rightarrow c\bar{c}$  [1,26]. Within an expanding fireball model (see below) we follow the dynamical picture, accounting, however, for a reduced  $J/\Psi$  binding energy. The dissociation rate is calculated from

$$\Gamma_{diss} = \sum_{i=q,g} \int_{k_{min}}^{\infty} \frac{d^3k}{(2\pi)^3} f^i(k;T) \sigma_{diss}(s) \quad (1)$$

with  $k_{min}$  denoting the minimal on-shell momentum of a quark or gluon from the heat bath necessary to dissolve an in-medium charmonium bound state into a (free)  $c\bar{c}$  pair. The binding is characterized by a temperature-dependent dissociation energy  $E_{diss}$  taken from Ref. [27] using a Debye screening mass  $m_D^2 = g^2 T^2$  with a typical  $g \simeq 1.7$ ; this entails  $E_{diss}(T = 180 \text{ MeV}) \simeq 220$  MeV, dropping to  $\simeq 100$  MeV at  $T = 240$  MeV but crossing zero only around  $T_{Debye} \simeq 400$  MeV. With such a decrease in the  $J/\Psi$  binding energy, the break-up kinematics render the photo-dissociation process increasingly inefficient. For a loosely bound charmonium state, a more important mechanism turns out to be given by inelastic parton scattering,  $g(q, \bar{q}) + J/\Psi \rightarrow g(q, \bar{q}) + c + \bar{c}$ . We evaluate the respective cross sections in quasifree approximation using leading-order QCD [28] for  $gc \rightarrow gc$  ( $gc \rightarrow qc$ ) and the appropriate break-up kinematics. In addition to a gluon screening mass, thermal quasiparticle masses for light quarks ( $m_{u,d}^2 = g^2 T^2/6$ ,  $m_s^2 = m_0^2 + g^2 T^2/6$ ) and gluons ( $m_g^2 = g^2 T^2/2$ ) [29] are included. The resulting dissociation times,  $\tau_{diss} = \Gamma_{diss}^{-1}$ , are shown in Fig. 1 and compared to calculations with a constant break-up cross section of 1.5 mb, as well as to the photo-dissociation mechanism *without* medium effects in the  $J/\Psi$  bound state energy (as it has been employed in the literature

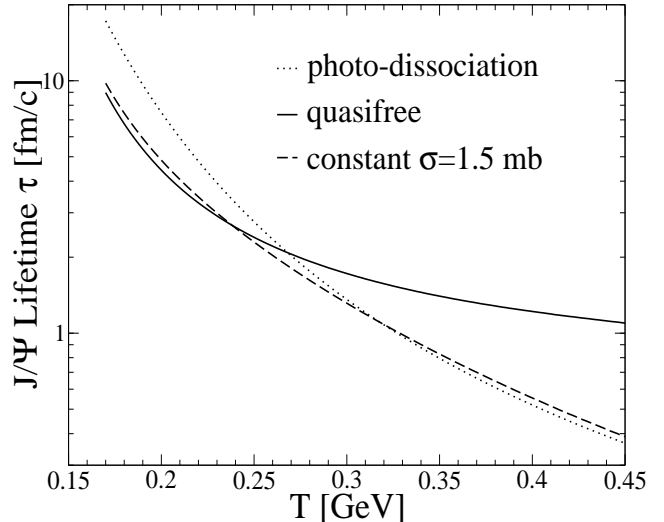


FIG. 1. Dissociation times for a  $J/\Psi$  in a QGP as a function of temperature. The full curve corresponds to the leading-order QCD process for quasifree  $g, q + c \rightarrow g, q + c$  scattering with *in-medium*  $J/\Psi$  bound state energy. The dashed curve represents a constant cross-section  $\sigma_{diss} = 1.5$  mb and the dotted curve results from photo-dissociation,  $gJ/\Psi \rightarrow c\bar{c}$ , assuming the *vacuum* dissociation energy.

before). At temperatures relevant for SpS conditions, the quasifree dissociation process (full line) is more efficient than photo-dissociation (dotted line). At higher temperatures, it becomes less efficient due to an increasing gluon screening mass which suppresses the  $t$ -channel exchange graphs for  $g(q, \bar{q}) + J/\Psi \rightarrow g(q, \bar{q}) + c + \bar{c}$ .

The temperature (time) dependence of the dissociation rate has to be coupled with a model for the space-time evolution of the reaction dynamics. To facilitate the calculations we here employ a thermal fireball description in line with earlier analyses of dilepton radiation at both SpS [16,30] and RHIC [31]. Let us briefly recall its essential elements. After initial impact of two colliding  $Au$  (or  $Pb$ ) nuclei the system is assumed to be thermalized after a formation time  $\tau_0$ . Thereafter, the fireball undergoes isentropic expansion characterized by conserved entropy and (net) baryon number which defines a thermodynamic trajectory in the  $\mu_B - T$  plane of the phase diagram. Above the critical temperature  $T_c$  a (quasiparticle) QGP equation of state is used, and a resonance hadron gas one below. The transition is modeled by a standard mixed phase construction [32],

$$S/V(t) = f s_{HG}(T_c) + (1 - f) s_{QGP}(T_c), \quad (2)$$

justified for a sufficiently sharp increase of the entropy density around  $T_c$  ( $f$ : fraction of matter in the hadronic phase,  $s_{HG}$  ( $s_{QGP}$ ): entropy density in the hadronic (plasma) phase).  $S$  denotes the total entropy in the considered rapidity interval, and  $V(t)$  the time dependent volume therein, which we simulate by two fireballs with cylindrical expansion as

$$V(t) = 2 \left( z_0 + v_z t + a_z \frac{t^2}{2} \right) \pi \left( r_\perp + a_\perp \frac{t^2}{2} \right)^2. \quad (3)$$

The parameters  $\{v_z, a_z, a_\perp\}$  are adjusted to finally observed flow velocities in connection with total fireball lifetimes of around 15 fm/c. The  $\sqrt{s}$ -dependence of the collisions is constructed as follows: the formation time  $\tau_0$  is taken to be  $\sim 1$  fm/c at SpS and  $\sim \frac{1}{3}$  fm/c at full RHIC energy (with a powerlike interpolation in  $\sqrt{s}$ ), resulting in initial temperatures of  $T_0 \simeq 205$  MeV and 390 MeV, respectively. We assume the transition temperature  $T_c$  to smoothly increase from  $T_c = 170$  MeV at  $\sqrt{s} = 17.3$  GeV to  $T_c = 180$  MeV at  $\sqrt{s} = 200$  GeV (with approximately constant critical entropy density in the hadronic phase). SpS and first RHIC data (at  $\sqrt{s} = 56$  GeV and 130 GeV) on total multiplicities [33] and  $\bar{p}/p$ ,  $\bar{\Lambda}/\Lambda$  ratios [34] are used to estimate the total entropy as well as baryon and strange-quark chemical potentials. This description of the collision gives results consistent with hydrodynamical calculations, *e.g.*, a pure QGP lifetime of  $\sim 1.5$  fm/c (3.5 fm/c) at SpS (RHIC), and a mixed phase until  $\sim 5$  fm/c (7.5 fm/c). The QGP suppression factor  $\mathcal{S}_{QGP}$  of  $J/\Psi$  mesons follows from integrating the dissociation rate over the space-time evolution. The resulting direct yields per central collision (including nuclear absorption) are listed in Tab. I.

The second source of charmonium states originates from thermal production at hadronization<sup>†</sup>. The underlying picture [13] is a statistical coalescence of  $c$  and  $\bar{c}$  quarks at  $T_c$ . In thermal models, hadron production is determined by the available phase space at  $T_c$ . The total number of particle species  $j$  then is

$$N_j = \frac{d_j V}{2\pi^2} \int_0^\infty p^2 dp \left[ \exp \left( \frac{\sqrt{p^2 + m_j^2} - \mu_j}{T} \right) \pm 1 \right]^{-1}, \quad (4)$$

where  $d_j$  denotes the degeneracy factor,  $\mu_j$  the pertinent chemical potential,  $\mu_j = B_j \mu_B + s_j \mu_s + c_j \mu_c$ , and  $V$  the hadronic fireball volume at  $T_c$ . Since at CERN-SpS  $N_{c\bar{c}} \ll 1$ , exact charm conservation is enforced within a canonical-ensemble treatment (see, *e.g.*, Refs. [35,36]). We include all known charmed hadrons [37] and fix the number  $N_{c\bar{c}}^{dir}$  of  $c\bar{c}$  pairs from primordial  $NN$  collisions in our restricted rapidity range as given by PYTHIA computations [38] upscaled by an empirical  $K$  factor,

<sup>†</sup>In principle,  $J/\Psi$  formation can also occur above  $T_c$  [18] through the reverse of the dissociation process, *i.e.*,  $c\bar{c}g \rightarrow J/\Psi g$ ; however, due to the smallness of the  $J/\Psi$  binding energy in the plasma, implying large formation times, we neglect formation above  $T_c$ , thus possibly underestimating thermal production somewhat.

$K \simeq 5$  [39]. This necessitates the introduction of a fugacity  $\gamma_c = \gamma_{\bar{c}}$  for charm and anticharm quarks according to

$$N_{c\bar{c}}^{dir} = \frac{1}{2} \gamma_c N_{open} \frac{I_1(\gamma_c N_{open})}{I_0(\gamma_c N_{open})} + \gamma_c^2 N_{hidden}, \quad (5)$$

where  $N_{open}$  ( $N_{hidden}$ ) denotes the thermal abundance of open (hidden) charm hadrons ( $I_{0,1}$  are modified Bessel functions). Hence, the total contribution to statistical  $J/\Psi$  production (including strong and electromagnetic feeddown) follows as  $\langle J/\Psi \rangle = \gamma_c^2 N_{J/\Psi}^{tot}$ , cf. Tab. I for selected collision energies.

$\sqrt{s}$ [GeV]	17.3	56	130	200
$\mathcal{S}_{QGP}$	0.66	0.50	0.33	0.23
$N_{J/\Psi}^{dir}$ [ $10^{-3}$ ]	0.45	2.41	3.68	3.25
$N_{c\bar{c}}^{dir}$	0.17	2.34	7.53	10.86
$\gamma_c$	0.82	2.46	4.85	5.62
$\langle J/\Psi \rangle$ [ $10^{-3}$ ]	0.16	4.31	27.30	45.22

TABLE I. Direct and statistical production of  $J/\Psi$ 's per central collision ( $N_p = 360$ ) at various  $\sqrt{s}$  energies in a fixed rapidity window covered by two fireballs.  $N_{J/\Psi}^{dir}$ : number of primordial  $J/\Psi$ 's remaining after nuclear absorption and plasma suppression ( $\mathcal{S}_{QGP}$ ).  $\gamma_c$ : charm quark fugacity deduced from (5) based on  $N_{c\bar{c}}^{dir}$  primordial  $c\bar{c}$  pairs.  $\langle J/\Psi \rangle$ : number of statistically produced  $J/\Psi$ 's.

Combining the two sources of  $J/\Psi$ 's (the suppressed direct as well as the statistical (or thermal) production), we calculate excitation functions from SpS to RHIC energies. Fig. 2 displays the ratio of the observed number of  $J/\Psi$ 's over the primordially produced one. The ther-

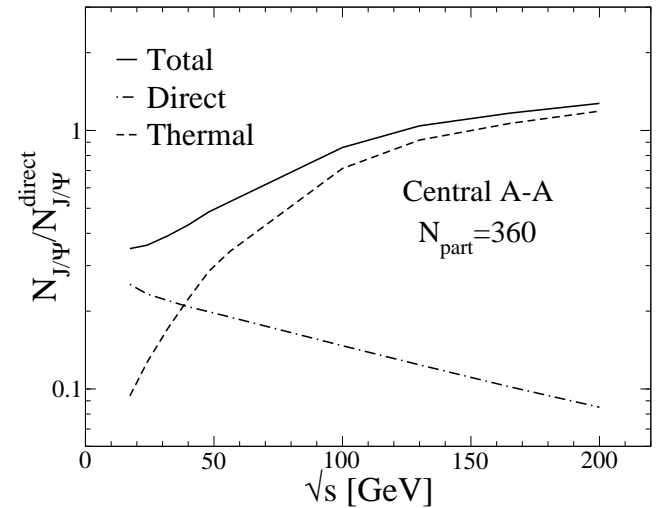


FIG. 2. Ratio of the number of observed  $J/\Psi$ 's over the number of primordially produced ones (full curve) in a two-fireball model around midrapidity. The dashed (dash-dotted) curve corresponds to the  $J/\Psi$  yield from statistical coalescence at hadronization (direct production with nuclear absorption and QGP suppression).

mal source accounts for one fourth of the yield at SpS, but dominates at higher energies implying a possible  $J/\Psi$  enhancement at RHIC [13,18].

In anticipation of open-charm measurements at both RHIC and SpS [40], one can make closer contact to observables by plotting the ratio of the final number of  $J/\Psi$ 's over the primordial number of  $c\bar{c}$  pairs, cf. Fig. 3. This ratio exhibits a minimum for  $\sqrt{s} \simeq 30$  GeV when

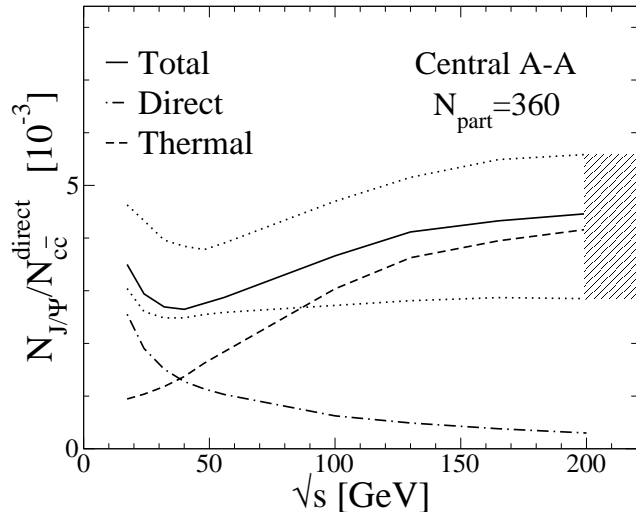


FIG. 3. Ratio of the number of observed  $J/\Psi$ 's over the number of primordial  $c\bar{c}$  pairs (full curve) in a two-fireball model around midrapidity. The dashed (dash-dotted) curve shows the statistical contribution (direct production with nuclear and QGP suppression) to this ratio. The band enclosed by the dotted lines reflects the uncertainty on the initial charm and  $J/\Psi$  production as explained in the text.

the thermal and direct contributions are about equal. A similar minimum structure has been found in Ref. [41], where, however, the  $J/\Psi$  yield at all energies was entirely attributed to statistical production.

The largest sensitivity in our calculation is attached to primordial  $c\bar{c}$  production as indicated by the band enclosed by the dotted lines in Fig. 3. The lower limit is estimated from next-to-leading order pQCD calculations [42] in connection with a lower bound in  $J/\Psi$  production from available data (supplemented by a phenomenological fit at higher energies [43]). The upper limit is obtained from a PYTHIA calculation for  $c\bar{c}$  production using GRV-HO structure functions (which tends to give the largest yield towards RHIC energies) in connection with  $J/\Psi$  production from Ref. [23]. We also checked that there is only moderate sensitivity to variations in the hadronization temperature: decreasing  $T_c$  to 170 MeV at  $\sqrt{s} = 200$  GeV (with an accompanying increase in the hadronization volume, but at fixed  $N_{c\bar{c}}$ ) entails a 10% larger yield of thermal  $J/\Psi$ 's (the decrease in the thermal density is overcompensated by the increase in volume and, more importantly, by the higher charm-quark fugacities). Within the uncertainties the plotted

ratio persists to exhibit a very different behavior (*i.e.*, an increase with  $CMS$  energy) from the one expected in the standard scenario of  $J/\Psi$  suppression.

Finally, we investigate the sensitivity of the minimum structure with respect to different QGP suppression mechanisms. Upon replacing the quasifree destruction process by the gluon photo-dissociation process shown in Fig. 1 (dotted line), we observe a slight overall increase in the yield without significant alteration of the shape. Thirdly, in a more extreme scenario based on Debye-screening, we assume  $J/\Psi$  mesons to be entirely suppressed if they are formed in a region with initial energy density  $\epsilon_0(r) > \epsilon_{Debye}$  (along the lines of Ref. [44]). Within the Glauber model, the spatial distribution of primordial  $J/\Psi$ 's is inferred from the nuclear thickness function  $T_{AB}(r)$  (characterizing the number of  $N-N$  collisions), whereas the energy-density profile is taken to be proportional to the density of participants in the transverse plane. We fix  $\epsilon_{Debye}$  to obtain a suppression consistent with the NA50 data at  $\sqrt{s} = 17.3$  GeV (translating into  $T_{Debye} \simeq 220$  MeV). As expected, the pertinent excitation function exhibits a stronger suppression pattern with increasing  $\sqrt{s}$ , generating a more pronounced minimum structure (at similar position) in the ratios  $N_{J/\Psi}/N_{J/\Psi}^{dir}$  and  $N_{J/\Psi}/N_{c\bar{c}}^{dir}$  than found with dynamical dissociation processes, cf. Fig. 4.

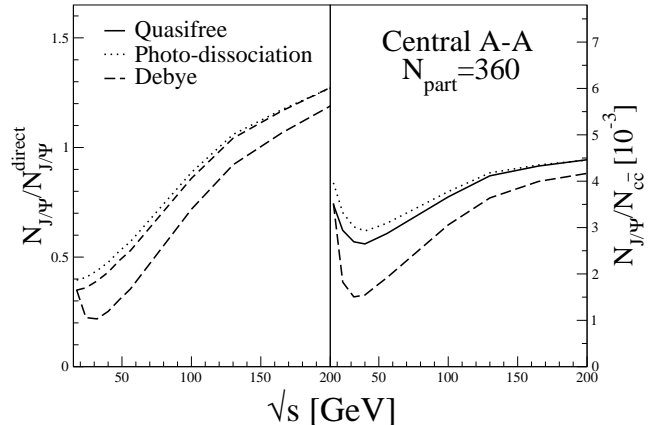


FIG. 4. Comparison of Debye-screening (dashed curves), photo-dissociation (dotted curves) and quasifree dissociation (full curves) of  $J/\Psi$ 's in a thermalized QGP at various collision energies, combined with thermal production. Photo-dissociation (with vacuum  $J/\Psi$  binding energy) gives results very similar to quasifree suppression (with in-medium  $E_{diss}$ ) whereas Debye screening induces stronger suppression reflected in a more pronounced minimum around  $\sqrt{s} = 30$  GeV.

In summary, we have proposed a “combined” approach to evaluate  $J/\Psi$  yields in heavy-ion collisions which includes (i) a direct contribution of prompt  $J/\Psi$ 's subject to nuclear and Quark-Gluon Plasma absorption and,

(ii) a thermal contribution of  $J/\Psi$ 's emerging from recombination of  $c$  and  $\bar{c}$  quarks at hadronization. The employed framework is consistent with earlier calculations of thermal dilepton spectra; in particular, no enhancement in open-charm production has been invoked. The resulting  $J/\Psi$  excitation function exhibits a transition from mostly primordial to dominantly thermal production when going from SpS to RHIC. Such an interplay could be mapped out by a systematic variation in collision energies accessible at RHIC. The predicted increase in  $J/\Psi$  yields will render  $J/\Psi$  suppression difficult to identify as a QGP signature. However, the excitation function might serve as a sensitive probe of the hadronization dynamics at the QCD phase transition, provided an accurate knowledge of primordial  $c\bar{c}$  abundances. We also note that our description might imply significant changes in the  $J/\Psi$  transverse-momentum distributions. At the highest RHIC energies, one expects essentially thermal shapes (accompanied by a flow component from the QGP phase), which should be distinguishable from hard production prevalent at the SpS.

In this work, we did not address phenomena in the later hadronic stages of the collision, *e.g.*, possible consequences of (the approach towards) chiral symmetry restoration via in-medium modifications of  $D$ -meson masses which might play an important role for the  $\Psi'/\Psi$  ratio [45,46]. An extension of our approach along these lines together with a detailed comparison to available data on centrality and projectile dependence is in progress [47].

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